3

The Organization and Functions of the Nervous System

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After reading this chapter, you will be able to

3.1 Identify the components of the central nervous system.

3.2 Name the structures in the forebrain, midbrain, and hindbrain.

3.3 Predict how damage to specific brain structures will impact specific behaviors.

3.4 Describe the components that protect the brain from damage.

3.5 Examine the functions of the peripheral nervous system divisions.

3.6 Explain how the peripheral and central nervous systems interact in generating experiences and behavior.

3.7 Summarize the changes that the nervous system undergoes during typical development.

3.8 Illustrate the changes that occur in the nervous system as the result of experience.

Karen is a college graduate and holds a job with considerable responsibility. She is married and leads a normal life except for occasional epileptic seizures. When her doctors ordered a brain scan to find the cause of her seizures, they were astounded. The normal person's brain has many folds on its surface, so it is wrinkled like a walnut; Karen's is perfectly smooth, like the one on the right in Figure 3.1. Notice, too, that the dark areas in the middle of the brain (ventricles) are enlarged, indicating a deficiency in the amount of brain tissue. People with her disorder are usually not only *lissencephalic* (literally, *smooth-brained*) and epileptic like Karen but severely impaired intellectually as well (Barinaga, 1996; Eksioglu et al., 1996). So what really amazed Karen's doctors was not how abnormal her brain is but that she lived past childhood and that she functions not just normally but well above average. How do we explain why some people are able to escape the consequences of what is usually a devastating developmental error? The answer is that we do not know why; it is one of the mysteries that neuroscientists are attempting to solve in order to understand the brain's remarkable resilience.

You are now well versed in the functioning of neurons and how they interact with each other. What you need to understand next is how neurons are

FIGURE 3.1 A Normal Brain and a Lissencephalic Brain.

Source: Courtesy of Dr. Joseph Gleeson, University of California San Diego School of Medicine.

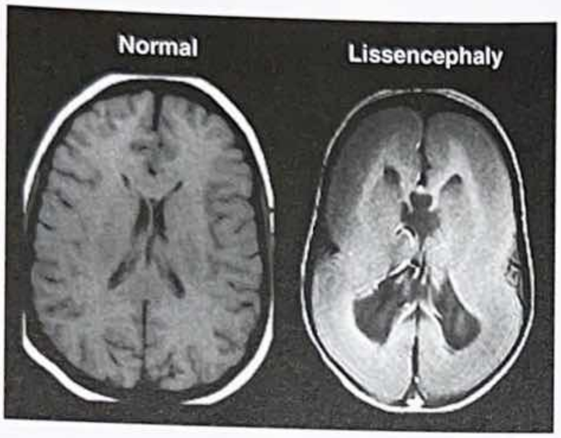
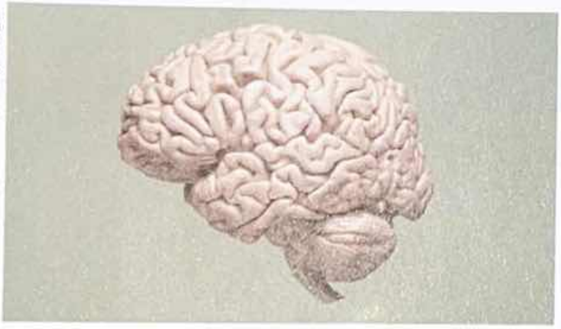


FIGURE 3.2 View of a Human Brain.



Chris Parsons / DigitalVision / Getty Images

grouped into the functional components that make up the nervous system. In the next few sections, we will review the physical structure of the nervous system so that you will have a road map for more detailed study in later chapters. We will also include an overview of major functions to prepare you for the more detailed treatments to come in later chapters. First, we will look at the two divisions of the nervous system before turning our attention to issues such as brain development and change.

The Central Nervous System

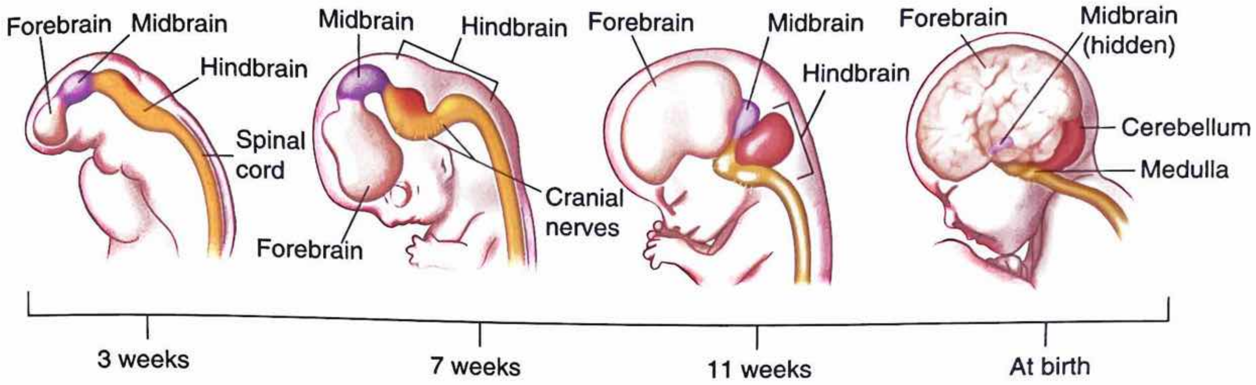
The nervous system is divided into two subsystems. The *central nervous system (CNS)* includes the brain and the spinal cord. The second part is the peripheral nervous system (PNS), which we will examine later in the chapter. Before we go any further, we need to be sure you understand a couple of terms correctly. As we talk about the nervous system, be careful not to confuse *nerve* and *neuron*. A neuron is a single neural cell; a *nerve* is a bundle of axons (the long processes extending from neurons' cell bodies) running together like a multiwire cable. However, the term *nerve* is used only in the peripheral nervous system; inside the CNS, bundles of axons are called *tracts*. Most of the neurons' cell bodies are also clustered in groups; a group of cell bodies is called a *nucleus* in the CNS and a *ganglion* in the PNS. Table 3.1 should help you keep these terms straight.

Figure 3.2 is a photograph of a human brain. It will be easier to visualize the various structures of the brain if you understand that the CNS begins as a hollow tube and preserves that shape as it develops (Figure 3.3). The upper end of the tube develops three swellings, which will become the forebrain, midbrain, and hindbrain; the lower part of the tube develops into the spinal cord. The forebrain appears to be perched on top of the lower structures as it enlarges and almost completely engulfs them. By comparing the four drawings in this series, you can see that the mature forebrain obscures much of the lower brain from view. You will get a better idea of these hidden structures later when we look at an interior view of the brain.

TABLE 3.1 Terms for Axons and Cell Bodies in the Nervous System.

	PERIPHERAL	CENTRAL
Bundle of axons	Nerve	Tract
Group of cell bodies	Ganglion	Nucleus

FIGURE 3.3 The Brain Develops From a Tubular Structure.



The Forebrain

The major structures of the forebrain are the two cerebral hemispheres, the thalamus, and the hypothalamus. The outer layer of the hemispheres, the cortex, is where the highest-level processing occurs in the brain.

THE CEREBRAL HEMISPHERES

The large, wrinkled *cerebral hemispheres* dominate the brain's appearance (Figure 3.4). They not only are large in relation to the rest of the brain but also are disproportionately larger in humans than in other primates (Deacon, 1990). The *longitudinal fissure* that runs the length of the brain separates the two cerebral hemispheres, which are nearly mirror images of each other in appearance. Often the same area in each hemisphere has identical functions as well, but you will see in later chapters that this is not always the case. The simplest form of *asymmetry* is that each hemisphere receives most of its sensory input from the *opposite* side of the body (or of the world, in the case of hearing and vision) and provides most of the control of the opposite side of the body.

Look again at Figures 3.2 and 3.4. The brain's surface has many ridges and grooves that give it a very wrinkled appearance; the term we use is *convoluted*. Each ridge is called a *gyrus*; the groove or space between two gyri is called a *sulcus* or, if it is large, a *fissure*. You can see how the gyri are structured in the cross section of a brain in Figure 3.5. The outer surface is the *cortex* (literally, "bark"), which is made up mostly of the cell bodies of neurons; because cell bodies lack myelin, the cortex looks grayish in color, which is why it is referred to as gray matter. Remember that neural processing occurs where neurons synapse onto other neurons, which indicates why the cortex is so important. The cortex is only 1.5 to 4 millimeters (mm) thick, but the convolutions increase the amount of cortex by tripling the surface area. The convolutions also provide the axons with easier access to the cell bodies than if the developing cortex thickened instead of wrinkling. The axons come together in the central core of each gyrus, where their myelination gives the area a whitish appearance. Notice how the white matter of each

? Why is a wrinkled brain better than a smooth one?

FIGURE 3.4 Human Brain Viewed From Above.

This photo shows the cerebral hemispheres and longitudinal fissure. The blood vessels have been removed from the right hemisphere.

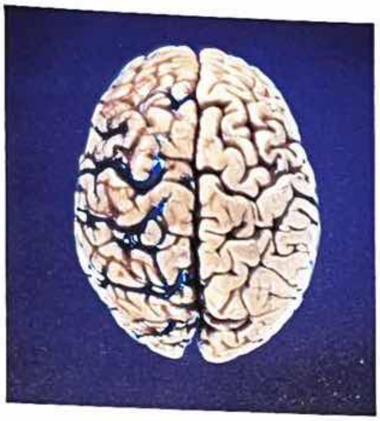


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FIGURE 3.5 Section of Human Brain Showing Gyri and Sulci.

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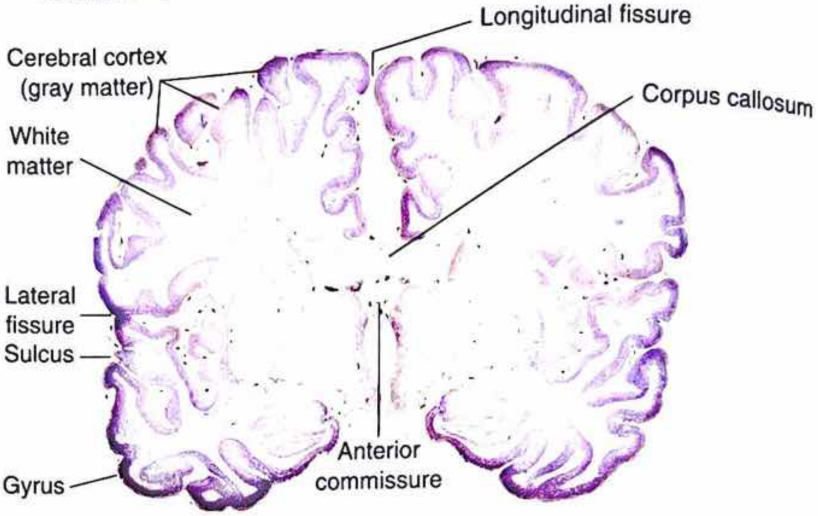


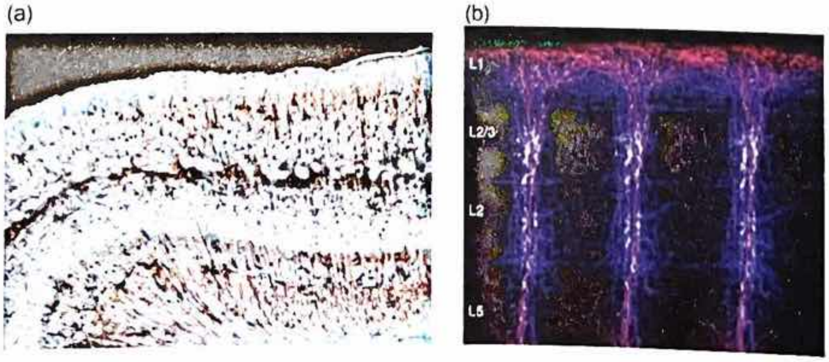
gyrus joins with the white matter of the next gyrus, creating the large bands of axons that serve as communication routes, both within each hemisphere and between the two hemispheres.

You've overslept, and now you find yourself running to your early morning test, fretting about being late while rehearsing answers to the questions you expect on the exam. You interrupt your thoughts only when you have to dodge a bicyclist; your heart rate increases even further with your anger at the student for riding on the sidewalk. Do you ever wonder how your brain pulls all this off?

FIGURE 3.6 Layers and Columns of the Cortex.

(a) Photograph of a section of the cortex, revealing its layered organization. (b) Photograph showing the columnar arrangement of cells in the cortex; the numbers on the left identify the cortical layers.

Source: (a) "Human-Specific Organization of Primary Visual Cortex: Alternating Compartments of Dense Cat-301 and Calbindin Immunoreactivity in Layer 4A," by Todd M. Preuss and Ghislaine Q. Coleman, *Cerebral Cortex, 12*(7), pp. 671–691, doi:10.1093/cercor/12.7.671. (b) Reconstructed neurons from the Blue Brain Project © BBP/EPFL.



It will take the rest of this text to *start* answering that question, but this is a good time to mention two ways the brain's organization helps it be more efficient. First, the cortex in humans and most mammals is arranged in layers; the number of layers is usually six, though a particular layer may be absent in some areas. The layers stand out from each other because they are separated by fibers that serve the cell bodies, but they also differ in appearance: They vary in type and size of cells and in the concentration of cell bodies versus axons (see Figure 3.6a). There are differences in function as well. Some researchers have concluded that Layer I is inhibitory, II and III are associational, IV is sensory, and V and VI have motor functions (Buxhoeveden & Casanova, 2002; Larkum, 2013).

Second, the cells of the cortex are organized into groups of 80 to 100 interconnected neurons, which are arranged in columns running perpendicular to the cortical surface (Figure 3.6b; Buxhoeveden & Casanova, 2002). They provide a vertical unification of the cortex's horizontal layers, which contributes to their role as the primary information-processing unit in the cortex (Torii, Hashimoto-Torii, Levitt, & Rakic, 2009). The cells in a column have a similar function; for example, they may receive input from the same area on the skin's surface, while surrounding columns serve adjacent locations. In the visual cortex, the cells in a column may detect object edges at a particular orientation, while surrounding columns respond to edges at a slightly different orientation. Having similar functions grouped close together in well-connected columns helps the brain work quickly and efficiently.

Students often ask whether intelligent people have bigger brains. Bischoff, the leading European anatomist in the 19th century, argued that the greater average weight of men's brains was infallible proof of their intellectual superiority over women. When he died, his brain was removed and added to his extensive collection, as his will had specified; ironically, it weighed only 1,245 grams (g), less than the average of about 1,250 g for women ("Proof?" 1942). There actually is a tendency for people with larger brains to be more intelligent (Willerman, Schultz, Rutledge, & Bigler, 1991), but the relationship is small and highly variable. What this means is that factors other than brain size are more important; otherwise, women would be less intelligent than men, as Bischoff claimed, but we know from research that this is not the case. When we look at brain size more closely in Chapter 13, you will learn that Einstein's brain was even smaller than Bischoff's.

When we look across species, brain size is more related to body size than to intelligence; the brains of elephants and sperm whales are five to six times larger than ours. It is a brain's complexity, not its size, that determines its intellectual power. Look at the brains in Figure 3.7, and then compare them with the human brain in Figure 3.2. You can see two features that distinguish more complex, more highly evolved brains from less complex ones. One is that the higher brains have more gyri, which means more surface area and, therefore, more cortex. The other is that the cerebral hemispheres are larger in proportion to the rest of the brain. It is no accident that the cerebral hemispheres are perched atop the rest of the brain and the spinal cord. The CNS is arranged in a *hierarchy*; as you ascend from the spinal cord through the hindbrain and midbrain to the forebrain, the neural structures become more complex, and so do the behaviors they control.

■ **FIGURE 3.7** Brains of Three Different Mammals.

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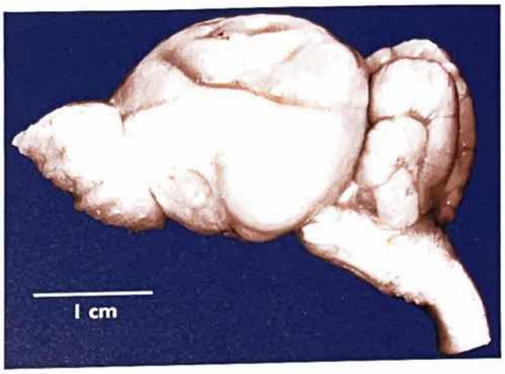
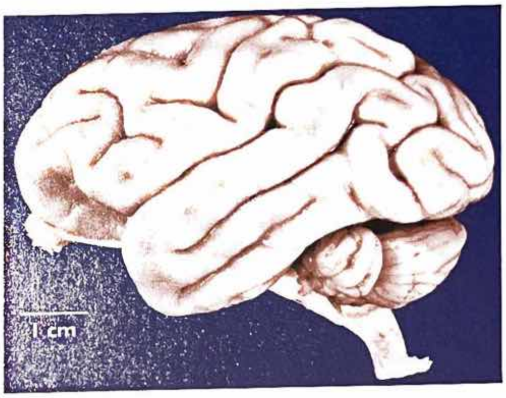
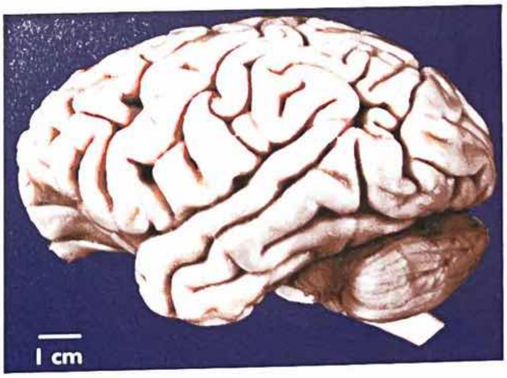


(a) Armadillo brain.



(b) Monkey brain.

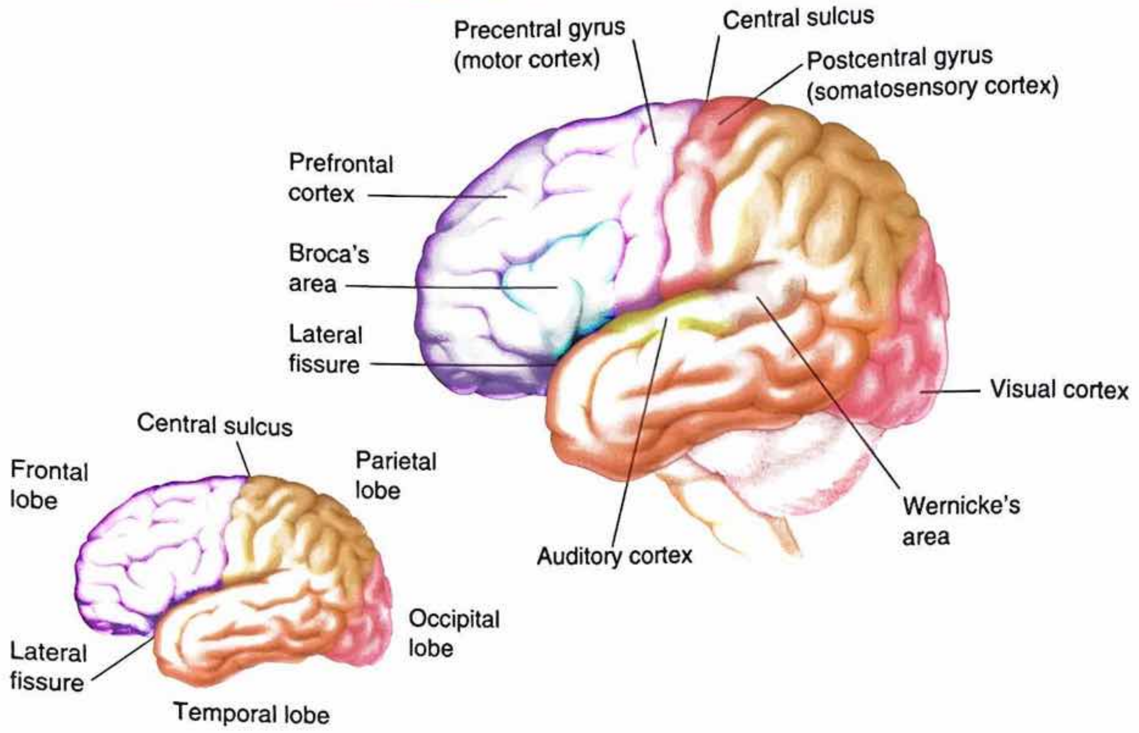


(c) Chimpanzee brain.

THE FOUR LOBES

The hemispheres are divided into four lobes—frontal, parietal, occipital, and temporal—each named after the skull bone covering it. The lobes are illustrated in Figure 3.8, along with the major functions located within them. These divisions are somewhat arbitrary, but they are very useful for locating structures and functions, so we will organize our discussion around them. Sometimes we need additional precision in locating structures, so you should get used to seeing the standard terms that are used; the most important ones are

FIGURE 3.8 Lobes and Functional Areas on the Surface of the Hemispheres.



illustrated in Figure 3.9a. Also, throughout this text, you will see illustrations of the nervous system from a variety of perspectives; until you get more comfortable with the structure of the nervous system, it may be difficult to tell what you are seeing. The images in Figure 3.9b will serve as a guide for understanding the orientation of most of these illustrations.

The *frontal lobe* is the area anterior to (in front of) the *central sulcus* and superior to (above) the *lateral fissure*. The functions here are complex and include some of the highest human capabilities. A considerable portion of the frontal lobes is also involved with the control of movement. And because the primary motor area is located along the posterior (rear) boundary of the frontal lobe, we start our discussion there. (You should continue to refer to Figure 3.8.)

? What functions are found in the frontal lobes?

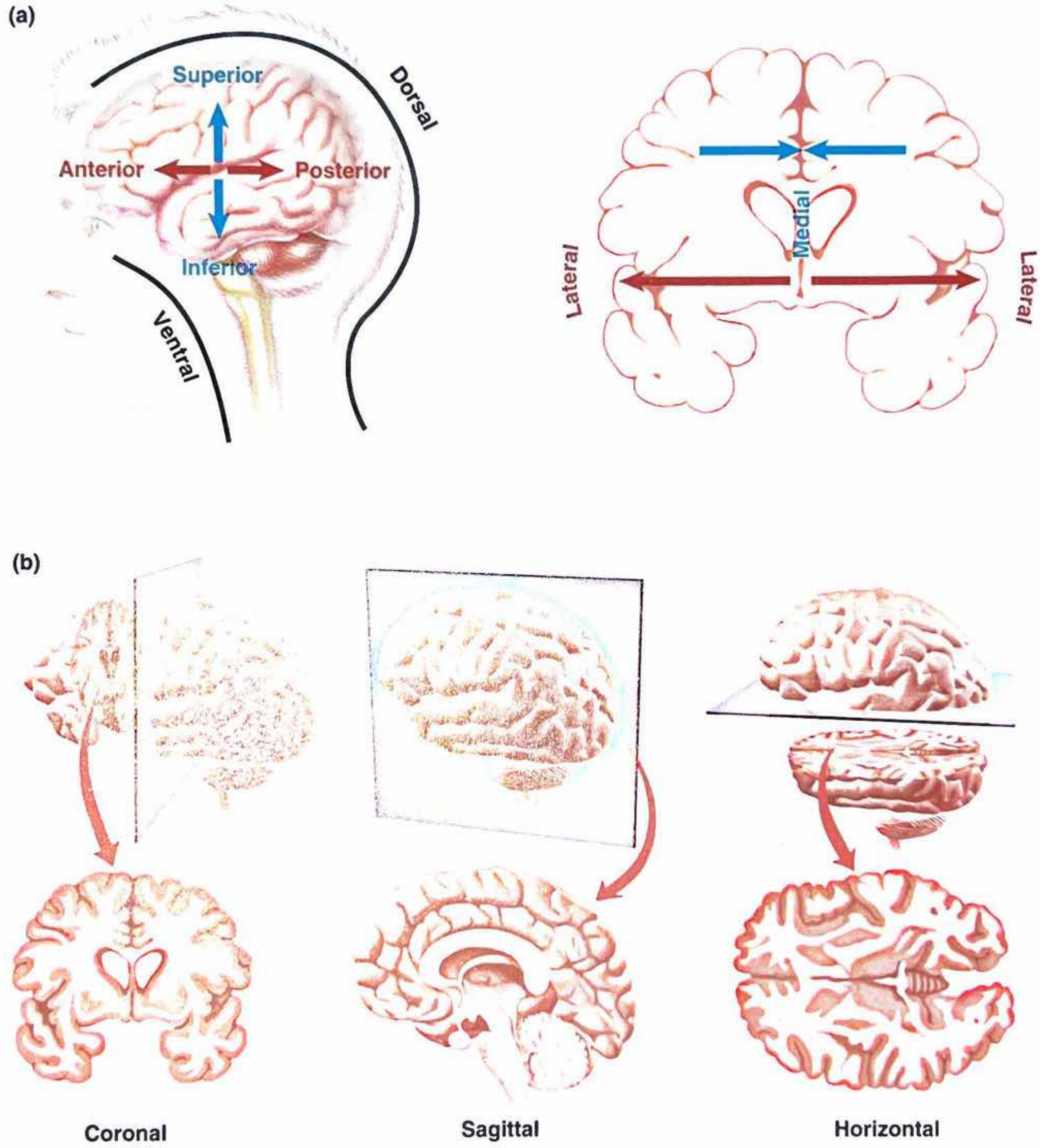
The *precentral gyrus*, which extends the length of the central sulcus, is the location of the primary *motor cortex*, which controls voluntary (nonreflexive) movements. The motor area in one hemisphere controls the opposite side of the body, though it does exert a lesser control over the same side of the body. The parts of the body are "mapped onto" the motor area of each hemisphere in the form of a *homunculus*, which means "little man." All this means is that the cells that control the muscles of the hand are adjacent to the cells controlling the muscles of the arm, which are next to those controlling the shoulder, and so on (Figure 3.10). The homunculus is distorted in shape, however; the parts of the body that make precise movements, such as the hands and fingers, have proportionally more cortex devoted to their control. The *primary motor cortex*, like other functional areas of the brain, carries out its work in concert with adjacent *secondary* areas. The secondary motor areas are located just anterior to the primary area. Subcortical (below the cortex) structures, such as the basal ganglia, also contribute to motor behavior. We will talk more about motor control in Chapter 11.

Looking back at Figure 3.8, locate Broca's area anterior to the motor area and along the lateral fissure. *Broca's area* controls speech production, contributing grammatical structure and the motor control involved in speech (via the motor cortex). A patient with damage to this area was asked about a dental appointment; he replied, haltingly, "Yes . . . Monday . . .

FIGURE 3.9 Terms Used to Indicate Direction and Orientation in the Nervous System.

(a) *Dorsal* means toward the back, and *ventral* means toward the stomach. (This terminology was developed with other animals and becomes more meaningful when you imagine the human on all fours, face forward. *Anterior* means toward the front, and *posterior* means toward the rear. *Superior* is a location above another structure, and *inferior* means below another structure. *Lateral* means toward the side; *medial* indicates toward the middle.

(b) The *coronal plane* divides the brain vertically from side to side, the *sagittal plane* divides it vertically in an anterior-posterior direction, and the *horizontal* plan divides it between the top and bottom. We use these terms when we refer to an image (e.g., a sagittal view) or when the brain is cut along one of these planes (e.g., a horizontal section).



Dad and Dick . . . Wednesday 9 o'clock . . . 10 o'clock . . . doctors . . . and . . . teeth" (Geschwind, 1979). Similar problems occur in reading and writing. In another example of hemispheric asymmetry, language activity is controlled mostly by the left hemisphere in 9 out of 10 people. More information about the neural basis of language control will be found in Chapter 9.

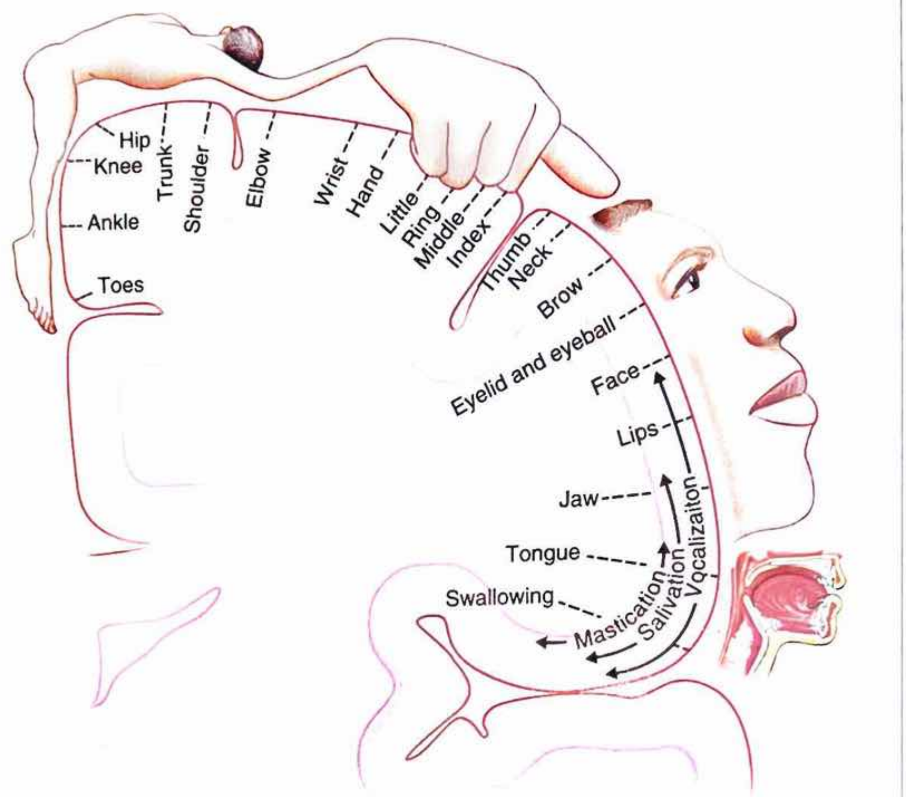


FIGURE 3.10 The Motor Cortex.

This view shows a cross section (coronal) of the precentral gyrus. The distorted body proportions and facial features of the homunculus indicate the relative amount of motor cortex devoted to those body areas.

Source: Adapted from W. Penfield and T. Rasmussen, The Cerebral Cortex of Man: A Clinical Study of Localization of Function. © 1950 Gale, a part of Cengage Learning, Inc.

The more anterior part of the frontal lobes—the prefrontal cortex in Figure 3.8—is functionally complex. It is the largest region in the human brain, twice as large as in chimpanzees, and it accounts for 29% of the total cortex (Andreasen et al., 1992; Deacon, 1990). The *prefrontal cortex* is involved in planning and organization of behavior, decision making, adjusting behavior in response to its consequences, and planning how to achieve goals (Bechara, Damasio, Tranel, & Damasio, 1997; Fuster, 1989; E. K. Miller & Cohen, 2001). Symptoms of impairment are varied, depending on which part of the prefrontal area is affected (Mesulam, 1986), but malfunction often strikes at the capabilities we consider most human. Schizophrenia and depression, for example, involve dysfunction in the prefrontal cortex.

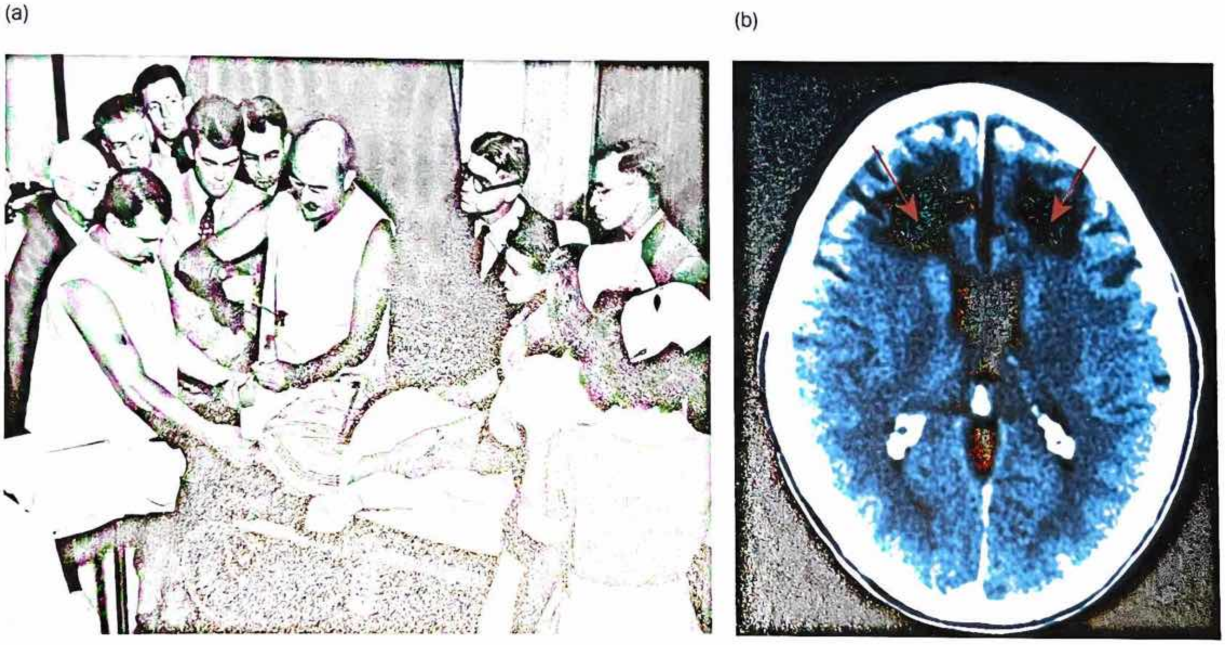
People with prefrontal damage often engage in behavior that normal individuals readily recognize will get them into trouble. In clinical interviews, they show good understanding of social and moral standards and the consequences of behavior—for example, they can describe several valid ways to develop a friendship, maintain a romantic relationship, or resolve an occupational difficulty—but they are unable to wisely choose among the options. In real life, they suffer loss of friends, financial disaster, and divorce (A. Damasio, 1994). Research indicates that prefrontal damage impairs the ability to learn from reward and punishment and to control impulses (Bechara et al., 1997). In addition, those with prefrontal damage have reduced behavioral flexibility with respect to choosing possible actions based on a particular situation (Ragozzino, 2007).

Despite the effects of frontal lobe damage, during the 1940s and 1950s, surgeons performed tens of thousands of *lobotomies*, a surgical procedure that disconnects the prefrontal area from the rest of the brain. Initially, lobotomies were performed only on patients with severe schizophrenia, but many overly enthusiastic doctors lobotomized patients with much milder problems. Walter Freeman, shown in Figure 3.11, did more than his share of the

FIGURE 3.11 Lobotomy Procedure and a Lobotomized Brain.

(a) Walter Freeman inserts his instrument between the eyelid and the eyeball, drives it through the skull with a mallet, and moves it back and forth to sever the connections between the prefrontal area and the rest of the brain. (b) A horizontal view of a brain shows the gaps (arrows) produced by a lobotomy.

Source: (a) © Living Art Enterprises, LLC/Science Source. (b) © Living Art Enterprises, LLC/Science Source.



40,000 lobotomies performed in the United States and zealously trained other psychiatrists in the technique (Valenstein, 1986). The surgery calmed agitated patients, but the benefits came at a high price; the patients often became emotionally blunted, distractible, and childlike in behavior. In a follow-up study of patient outcomes, 49% were still hospitalized, and less than a fourth of the others were living independently (A. Miller, 1967). Lack of success with lobotomy and the introduction of psychiatric drugs in the 1950s made the surgery a rare therapeutic choice. Now *psychosurgery*, the use of surgical intervention to treat cognitive and emotional disorders, is generally held in disfavor, unlike brain surgery to treat problems such as tumors. A Further Look describes the most famous case of accidental lobotomy.

The *parietal lobes* are located superior to the lateral fissure and between the central sulcus and the occipital lobe. The *primary somatosensory cortex*, located on the postcentral gyrus, processes the skin senses (touch, warmth, cold, and pain) and the senses that inform us about body position and movement (see Figure 3.8 again). Like the motor cortex, the somatosensory area serves primarily the opposite side of the body. The somatosensory cortex also is organized as a homunculus, but in this case, the size of each area depends on the sensitivity in that part of the body. When we discuss the senses of vision and hearing in later chapters, you will learn that this mapping is a general principle of brain organization. Also, this is a good place to point out that the sensory areas of the brain are often referred to as *projection areas*, as in *somatosensory projection area*.

? What functions are found in the parietal lobes?

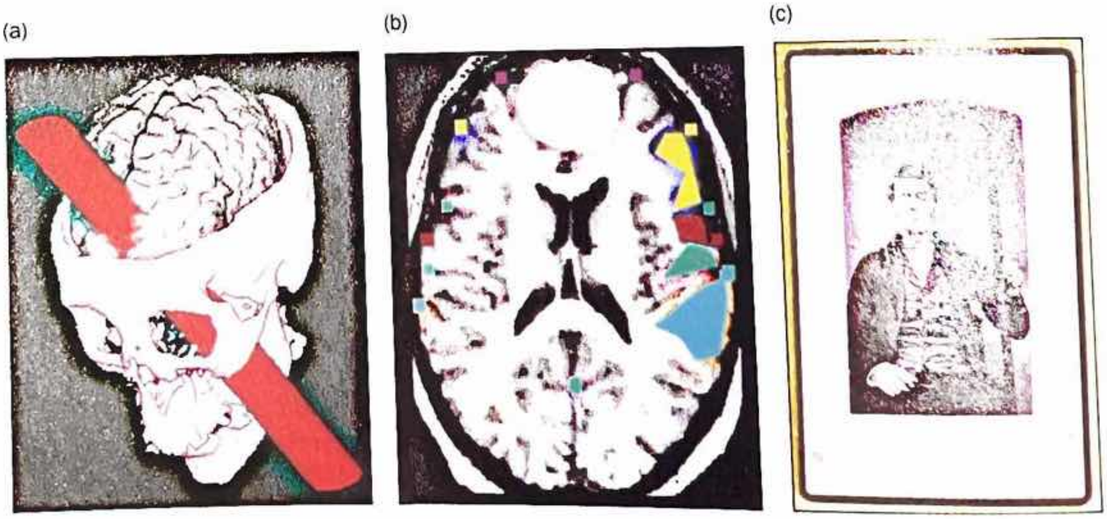
Each of the lobes contains *association areas*, which carry out further processing beyond what the primary area does, often combining information from other senses. Parietal lobe association areas, for example, receive input from the body senses and from vision; they help

A FURTHER LOOK

The Case of Phineas Gage

In 1848, Phineas Gage, a 25-year-old railroad construction foreman in Cavendish, Vermont, was tamping explosive powder into a blasting hole when the charge ignited prematurely and drove the 3.5-foot-long (1.15-m) tamping iron through his left cheek and out the top of his skull. Gage not only regained consciousness immediately and was able to talk and to walk with the aid of his men but also survived the accident with no impairment of speech, motor abilities, learning, memory, or intelligence. However, his personality was changed dramatically. He became irreverent and profane, and although Gage previously was the most capable man employed by the railroad, he no longer was dependable and had to be dismissed. He wandered about for a dozen years doing manual labor, never able to live fully independently, and died in the care of his family following seizures that apparently resulted from the injury.

Almost a century and a half later, Hanna Damasio and her colleagues carried out a belated postmortem examination of Gage's skull (H. Damasio, Grabowski, Frank, Galaburda, & Damasio, 1994). Combining measurements from the skull with a three-dimensional computer rendering of a human brain, they reconstructed the path of the tamping iron through Gage's brain (see the accompanying figure). They concluded that the accident damaged frontal lobe areas that are involved in processing emotion and making rational decisions in personal and social matters. More recently, Jack Van Horn and colleagues at UCLA extended Damasio's work by calculating how much the white matter pathways—the myelinated axons that create the circuitry of the brain—would have been damaged by Gage's accident (Van Horn et al., 2012). By simulating the injury using averaged scans of healthy men's brains, they calculated that damage was limited to about 4% of the cerebral cortex and limited to the left hemisphere but that the white matter pathways suffered greater damage, with more than 10% of the connections to other parts of the brain disrupted. At the time of Gage's accident, physiologists were debating whether different parts of the brain have specific functions or are equally competent in carrying out functions. Gage's experience had such an important influence in tipping the balance toward localization of function that in 1998 scientists from around the world gathered in Cavendish to commemorate the 150th anniversary of the event (G. Vogel, 1998).



(a) Gage's skull. (b) A rendering of Gage's skull, showing the likely path of the rod and the white matter pathways damaged. (c) Phineas Gage, with the tamping iron.

Sources: (a) and (b) Reprinted with permission from J. D. Van Horn et al., "Mapping Connectivity Damage in the Case of Phineas Gage," *PLoS ONE, 7*, e37454. © 2012. Reprinted by permission from PLoS ONE. (c) Public domain.

the person identify objects by touch, determine the location of the limbs, and locate objects in space. Damage to the posterior parietal cortex may produce *neglect*, a disorder in which the person ignores objects, people, and activity on the side opposite the damage. This occurs much more frequently when the damage is in the right parietal lobe. The person may fail to shave or apply makeup on the left side of the face. In some cases, a stroke patient with a paralyzed arm or leg will deny that anything is wrong and even claim that the affected limb belongs to someone else.

The lateral fissure separates the temporal lobe from the frontal and parietal lobes. The *temporal lobes* contain the auditory projection area, visual and auditory association areas, an additional language area, and structures important in learning and memory (see Figure 3.8). The *auditory cortex*, which receives sound information from the ears, lies on the superior (uppermost) gyrus of the temporal lobe, mostly hidden from view within the lateral fissure. Just posterior to the auditory cortex is *Wernicke's area*, an association area that interprets language input arriving from the nearby auditory and visual areas; it also generates spoken language through Broca's area and written language by way of the motor cortex. When Wernicke's area is damaged, the person has trouble understanding speech or writing; the person can still speak, but the speech is mostly meaningless. Like Broca's area, this structure is found in the left hemisphere in most people.

What functions are found in the temporal lobes?

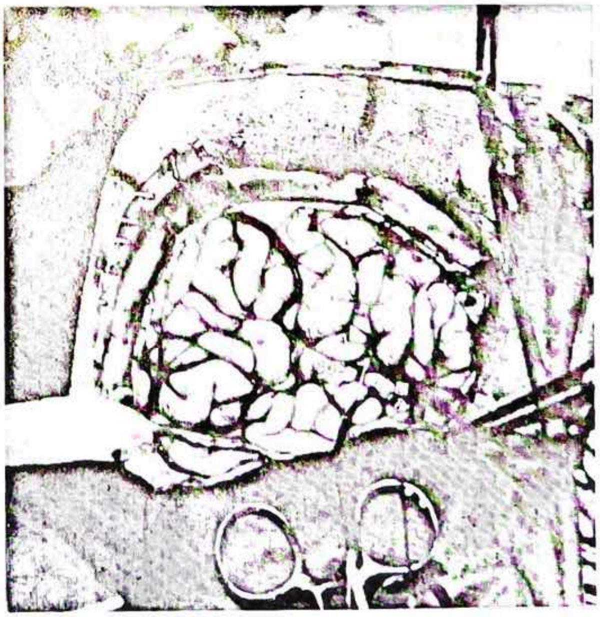
The *inferior temporal cortex*, in the lower part of the lobe, as the name implies, plays a major role in the visual identification of objects. People with damage in this area have difficulty recognizing familiar objects by sight, even though they can give detailed descriptions of the objects. They have no difficulty identifying the same items by touch. They may also fail to recognize the faces of friends and family members, though they can identify people by their voices. The neurologist Oliver Sacks (1990) described a patient who talked to parking meters, thinking they were children. Considering his strange behavior, it seems remarkable that he was unimpaired intellectually. As you read about cases like this one and hear of patients who do things like denying ownership of their paralyzed leg, you may begin to understand that human capabilities are somewhat independent of each other because they depend on different parts of the brain.

When the neurosurgeon Wilder Penfield (1955) stimulated patients' temporal lobes, he often elicited what appeared to be memories of visual and auditory experiences. Penfield was doing surgery to remove malfunctioning tissue that was causing epileptic seizures. Before the surgery, Penfield would stimulate the area with a weak electrical current and observe the effect; this allowed him to distinguish healthy tissue and important functional areas from the diseased tissue he wished to remove (Figure 3.12).

FIGURE 3.12 Brain of One of Penfield's Patients.

The numbered tags allowed Penfield to relate areas to patients' responses.

Source: From *The Excitable Cortex in Conscious Man*, by Wilder Penfield, 1958. Courtesy of Dennis Coon and Liverpool University Press, Liverpool, UK © 1958. Used with permission.



The patients were awake because their verbal report was needed for carrying out this mapping; because brain tissue has no pain receptors, patients required only a local anesthetic for the surgery. Stimulation of primary sensory areas provoked only unorganized, meaningless sensations, such as tingling, lights, or buzzing sounds. But when Penfield stimulated the association areas of the temporal cortex, 25% of the patients reported hearing music or familiar voices or, occasionally, reliving a familiar event. One time, the patient hummed along with the music she was "hearing," and the nurse, recognizing the tune, joined in by supplying the lyrics. (Does this not sound like a scene from a Monty Python movie—a sing-along during brain surgery?) People with epileptic activity or brain damage in their temporal lobes sometimes heard familiar tunes as well. Unfortunately, Penfield made no attempt to verify that the apparent memories were factual rather than a sort of electrically induced dream; we will see in Chapter 12, however, that the temporal lobe's role in memory is significant.

? What functions are found in the occipital lobes?

Finally, the *occipital lobes* are the location of the *visual cortex*, which is where visual information is processed (see Figure 3.8). The primary projection area occupies the posterior tip of each lobe; anterior to the primary area are four association areas that detect individual components of a scene, such as color, movement, and form; this information is then combined and processed further in other association areas, particularly in the temporal and parietal lobes. Just as the somatosensory and motor areas are organized to represent the shape of the body, the visual cortex contains a map of visual space because adjacent receptors in the back of the eye send neurons to adjacent cells in the visual cortex.

Now that you are familiar with the four lobes and some of the functions located in the cortex, we will direct our tour to structures below the surface.

THE THALAMUS AND HYPOTHALAMUS

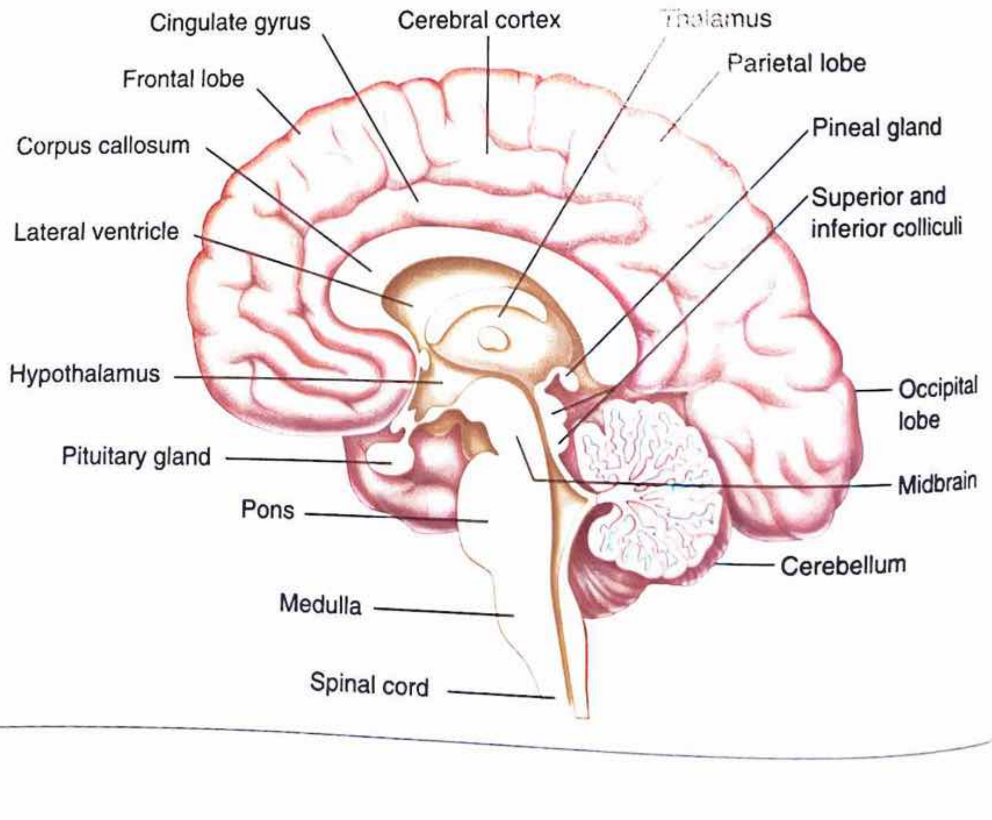
? What functions do the thalamus and hypothalamus perform?

Deep within the brain, the *thalamus* lies just below the lateral ventricles, where it receives information from all the sensory systems except olfaction (smell) and relays it to the respective cortical projection areas. (Figure 3.13 is a sagittal view of a brain sliced down the middle to show the structures described in this section.) Many other neurons from the thalamus project more diffusely throughout the cortex and help arouse the cortex when appropriate. There are actually two thalami, a right and a left, lying side by side. We will discuss additional functions for the structure in later chapters.

The *hypothalamus*, a smaller structure just inferior to the thalamus, plays a major role in controlling emotion and motivated behaviors, such as eating, drinking, and sexual activity (see Figure 3.13). The hypothalamus exerts this influence largely

FIGURE 3.13 Sagittal View of the Interior Features of the Human Brain.

In this view, the cut has been made between the cerebral hemispheres. Everything above the midbrain is forebrain; everything below is hindbrain.



through its control of the autonomic nervous system, which we will consider shortly. The hypothalamus also influences the body's hormonal environment through its control over the pituitary gland. In Figure 3.13, the pituitary appears to be hanging down on its stalk just below the hypothalamus. The pituitary is known as the *master gland* because its hormones control other glands in the body. The hypothalamus, which, like the thalamus, is paired, contains perhaps the largest concentration of nuclei important to behavior in the entire brain.

Just posterior to the thalamus is the pineal gland. You can see in Figure 3.13 why it was once called the "third eye" and was Descartes's best candidate for the seat of the soul (see Chapter 1): It is a single, unpaired structure, attached by its flexible stalk just below the hemispheres. In reality, the *pineal gland* secretes melatonin, a hormone that induces sleep; it controls seasonal cycles in nonhuman animals and participates with other structures in controlling daily rhythms in humans.

THE CORPUS CALLOSUM

If you were to look inside the longitudinal fissure between the two cerebral hemispheres, you would see that the hemispheres are distinctly separate from each other. A couple of inches below the brain's surface, the longitudinal fissure ends in the *corpus callosum*, a dense band of fibers that carry information between the hemispheres. The corpus callosum is visible in Figure 3.13; you can see it from another perspective, along with a smaller band of crossing fibers, the anterior commissure, by looking back at Figure 3.5. You know that the two hemispheres carry out somewhat different functions, so you can imagine that they must communicate with each other constantly to integrate their activities. In addition, incoming information is often directed to one hemisphere—visual information appearing to one side of your field of view goes to the hemisphere on the opposite side, just as information from one side of your body does. This information is "shared" with the other hemisphere through the crossing fibers, especially the corpus callosum; the car that is too close on your left is registered in your right hemisphere, but if you are steering with your right hand, it is your left hemisphere that must react.

Occasionally, surgeons have to sever the corpus callosum in patients with incapacitating epileptic seizures that cannot be controlled by drugs or other treatments. The surgery prevents the out-of-control neural activity in one hemisphere from engulfing the other hemisphere as well. The patient is then able to maintain consciousness during seizures and to lead a more normal life. These patients have been very useful for studying differences in the functions of the two hemispheres, because a stimulus can be presented to one hemisphere and the information will not be shared with the other hemisphere. Studies of these individuals have helped establish, for example, that the left hemisphere is more specialized for language than the right hemisphere and that the right hemisphere is better at spatial tasks and recognizing faces (Gazzaniga, 1967; Nebes, 1974). An example is shown in Figure 3.14. We will explore this topic further when we discuss consciousness in Chapter 15.

THE VENTRICLES

During development, the hollow interior of the nervous system develops into cavities called *ventricles* in the brain and the central canal in the spinal cord. The ventricles are filled with *cerebrospinal fluid*, which carries material from the blood vessels to the CNS and transports waste materials in the other direction. The *lateral ventricles* (Figures 3.13 and 3.15) extend forward deeply into the frontal lobes and in the other direction into the occipital lobes before they curve around into the temporal lobes. Below the lateral ventricles and connected to them is the *third ventricle*; it is located between the two thalami and the two halves of the hypothalamus, which form the ventricle's walls. The *fourth ventricle* is not in the forebrain, so we will locate it later.

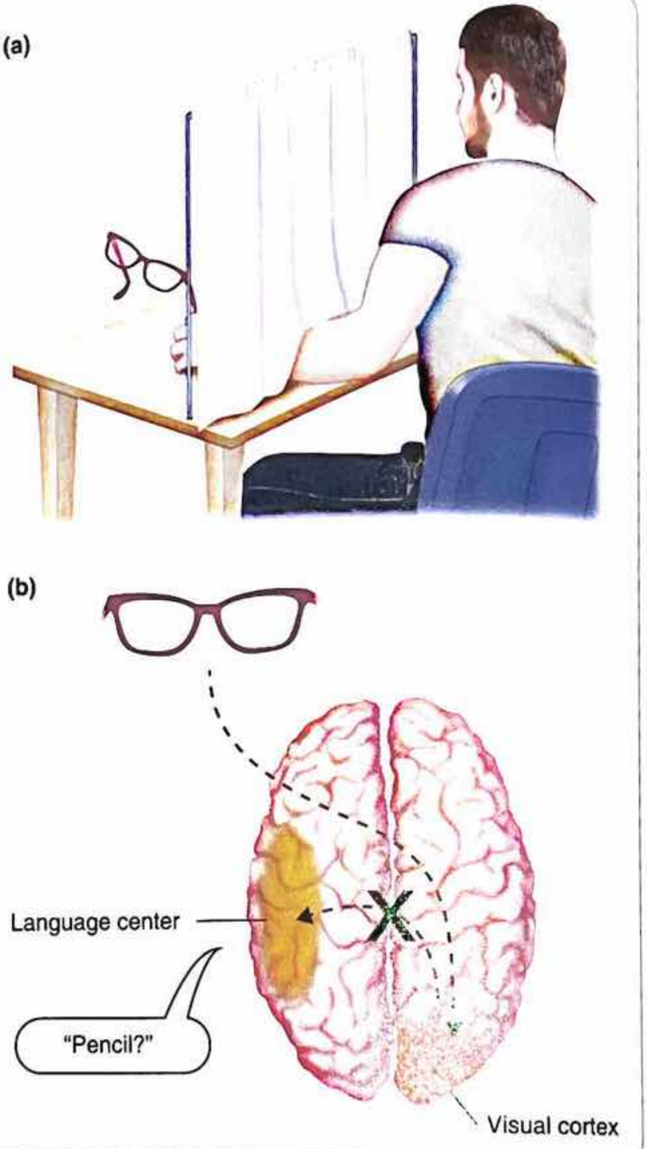
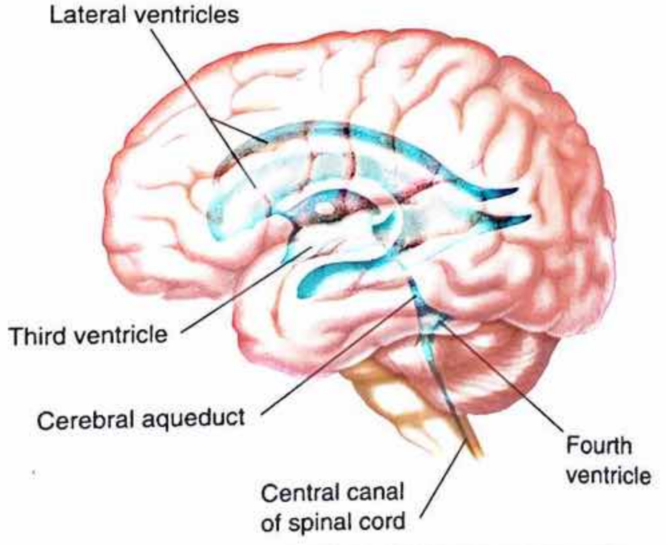


FIGURE 3.14 A Patient With Severed Corpus Callosum Identifying Objects by Touch.

He cannot say what the object is because the right hemisphere, which receives the information from the hand, has been disconnected from the more verbal left hemisphere. Results are similar for visually presented stimuli and sound information.

Carolina Hrejsa/Body Scientific Intl.

FIGURE 3.15 The Ventricles of the Brain.



The Midbrain and Hindbrain

The *midbrain* contains structures that have secondary roles in vision, hearing, and movement (Figures 3.13 and 3.16). The *superior colliculi*, for example, help guide eye movements and fixation of gaze, and the *inferior colliculi* help locate the direction of sounds. One of the structures involved in movement is the *substantia nigra*, which projects to the basal ganglia to integrate movements; its dopamine-releasing cells degenerate in Parkinson's disease (see Chapter 11). Another is the *ventral tegmental area*, which plays a role in the rewarding effects of food, sex, drugs, and so on (see Chapter 5). The midbrain also contains part of the reticular formation, which will be described shortly. Passing through the midbrain is the cerebral aqueduct, which connects the third ventricle above with the fourth ventricle below (see Figure 3.15). Notice in Figure 3.16 that the brain takes on a more obvious tubular shape here, reminding us of the CNS's origins. Considering the shape of these structures and the appearance of the cerebral hemispheres perched on top, you can see why this part of the brain is referred to as the *brain stem*.

The hindbrain is composed of the pons, the medulla, and the cerebellum (see Figures 3.13 and 3.16). The *pons* contains centers related to sleep and arousal, which are part of the reticular formation. The *reticular formation* is a collection of many nuclei running through the middle of the hindbrain and the midbrain; besides its role in sleep and arousal, it contributes to attention and to aspects of motor activity, including reflexes and muscle tone. The word *pons* means "bridge" in Latin, which reflects not only its appearance but also the fact that its fibers connect the two hemispheres of the cerebellum; the pons also has pathways connecting higher areas of the brain with the brain stem. The *medulla* forms the lower part of the hindbrain; its nuclei are involved with control of essential life processes, such as cardiovascular activity and respiration (breathing).

The cerebellum is the second most distinctive-appearing brain structure (see Figures 3.2, 3.8, 3.13, and 3.21). Perched on the back of the brain stem, it is wrinkled and divided down the middle like the cerebral hemispheres—thus its name, which means "little brain." The most obvious function of the *cerebellum* is refining movements initiated by the motor cortex by controlling their speed, intensity, and direction. A person with cerebellum damage has trouble making precise reaching movements and walks with difficulty because they lose the automatic patterning of movement routines. The cerebellum also plays a role in motor learning, and research implicates it in other cognitive processes, procedural memory, and emotion (Fiez, 1996). With 70% of the brain's neurons in its fist-sized volume, it would be surprising if it did not hold a number of mysteries waiting to be solved.

We have admittedly covered a large number of structures. It may help to see them and their major functions summarized in Table 3.2. But as you review these functions, remember the caveat about localization from Chapter 1 that a behavior is seldom the province of a single brain location but instead results from the interplay of networks of structures.

■ **FIGURE 3.16** The Brain Stem.

The brain stem includes posterior parts of the forebrain (thalamus, hypothalamus, etc.), the midbrain, and the hindbrain. The cerebellum has been removed to reveal the other structures. This is a dorsal view of the brain stem. Refer to Figure 3.13 for its orientation with respect to the entire brain.

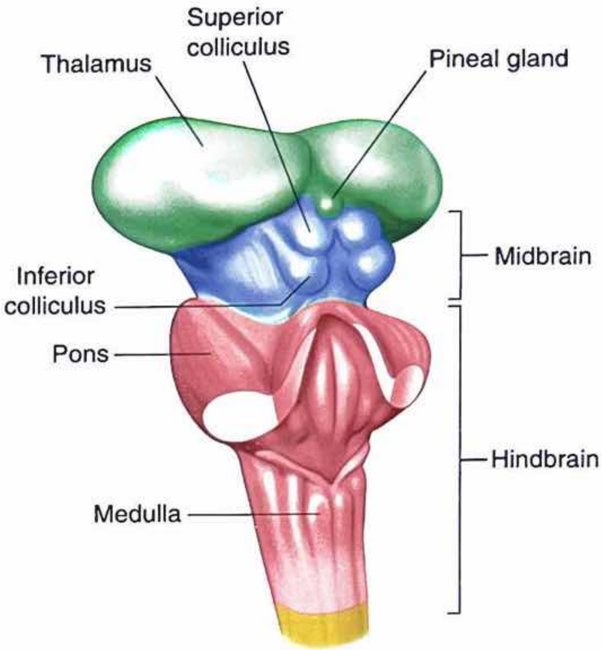


TABLE 3.2 Major Structures of the Brain and Their Functions.

STRUCTURE	MAJOR FUNCTION
Forebrain	
Frontal lobes	
Motor cortex	Plans and executes voluntary movements
Basal ganglia	Smooths movement generated by motor cortex
Broca's area	Controls speech; adds grammar
Prefrontal cortex	Involved in planning, impulse control

(Continued)

TABLE 3.2 (Continued)

STRUCTURE	MAJOR FUNCTION
Forebrain	
Parietal lobes	
Somatosensory cortex	Projection area for body senses
Association area	Location of body and objects in space
Temporal lobes	
Auditory cortex	Projection area for auditory information
Wernicke's area	Language area involved with meaning
Inferior temporal cortex	Visual identification of objects
Occipital lobes	
Primary visual cortex	Projection area for visual information
Visual association cortex	Processes components of visual information
Corpus callosum	Communication between the hemispheres
Ventricles	Contain cerebrospinal fluid
Thalamus	Relays sensory information to cortex
Hypothalamus	Coordinates emotional and motivational functions
Pineal gland	Controls daily and seasonal rhythms
Midbrain	
Superior colliculi	Role in vision—for example, eye movements
Inferior colliculi	Role in hearing, such as sound location
Substantia nigra	Integrates movement
Ventral tegmental area	Contributes to rewarding effects of food, sex, and drugs
Hindbrain	
Medulla	Reflexively controls life processes
Pons	Contains centers related to sleep and arousal
Reticular formation	Involved with sleep, arousal, attention, some motor functions
Cerebellum	Controls speed, intensity, direction of movements

The Spinal Cord

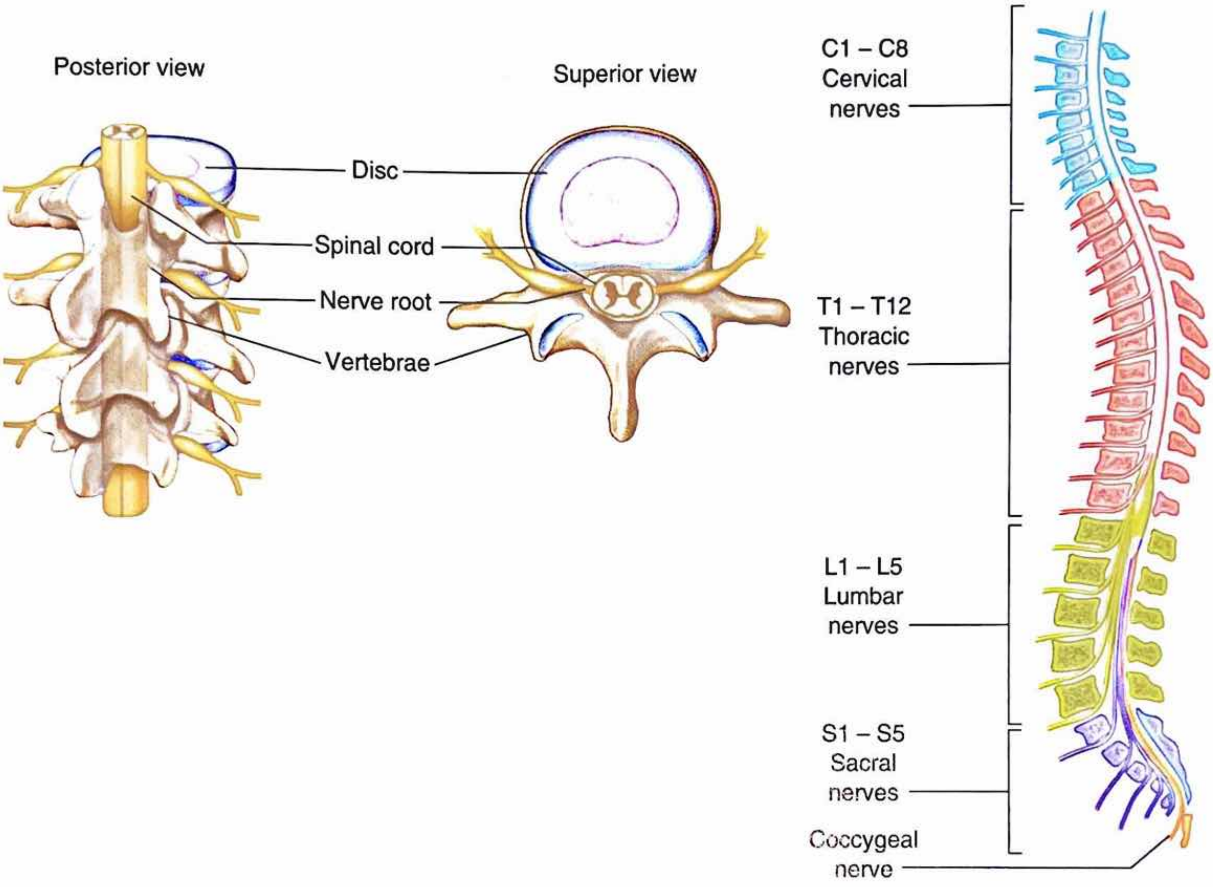
What is the structure of the spinal cord?

The *spinal cord* is a finger-sized cable of neurons that carries commands from the brain to the muscles and organs and sensory information into the brain. Its role is more complicated than that, though. It controls the rapid reflexive response when you withdraw your hand from a hot stove, and it contains pattern generators that help control routine behaviors such as walking. Notice the appearance of the interior of the spinal cord in Figure 3.17; it is arranged just the opposite of the brain, with the white matter on the outside and the gray matter in the interior. The white exterior is made up of myelinated axons—ascending sensory tracts on their way to the brain and descending motor tracts on their way to the muscles and organs.

Sensory neurons enter the spinal cord through the *dorsal root* of each spinal nerve. The sensory neurons are unipolar; clustering of their cell bodies in the dorsal root ganglion explains the dorsal root's enlargement. The sensory neuron in Figure 3.17 could be as much as 1 meter (m) long, with its other end out in a fingertip or a toe. The H-shaped structure in the middle of the spinal cord is made up mostly of unmyelinated cell bodies. The cell bodies of motor neurons are located in the *ventral horns*, which is why the ventral horns are enlarged. The axons of the motor neurons pass out of the spinal cord through the *ventral root*. The dorsal root and the ventral root on the same side of the cord join to form a spinal nerve that exits the spine between adjacent vertebrae (the bones that make up the spine).

FIGURE 3.17 Vertebral Column Anatomy.

Carolina Hrejsa/Body Scientific Intl.



Each spinal nerve carries information between the central nervous system and specific parts of the body (Figure 3.17). Nerves exiting the seven cervical vertebrae connect the head, neck, shoulders, and elbows. The nerves of the 12 thoracic vertebrae connect to the lower arms and upper torso, as well as the internal organs. The nerves from the five lumbar vertebrae innervate the intestines, legs, and feet. At the bottom, the five vertebrae of the sacrum are fused and target the hips and buttocks, and the tip of the spine (called the coccyx) connects solely to the rectum. Following a spinal injury, any connections between the body and the brain below the location of injury are impaired or lost. And any loss of cartilage between vertebral segments can cause compression of the exiting nerves, resulting in pain and impaired sensation to the body targets of that segment.

Most of the motor neurons receive their input from the brain, either from the motor cortex or from nuclei that control the activity of the internal organs. Notice in Figure 3.18, however, that in some cases, sensory neurons from the dorsal side connect with motor neurons, either directly or through an interneuron. This pathway produces a simple, automatic movement in response to a sensory stimulus; this is called a *reflex*. For example, when you touch a lighted match with your hand, the hot sensory signal travels to the spinal cord, where motor signals are directed out to the muscles of the arm to produce reflexive withdrawal. Many people use the term *reflex* incorrectly to refer to any rapid action a person takes without apparent thought; however, the term is limited to behaviors that are controlled by these direct sensory-motor connections. Besides not requiring thought, reflexive acts occur much more rapidly than the same response produced voluntarily. Reflexes originate in the brain as well as in the spinal cord, and reflexes also affect the internal environment—for example, reducing blood pressure when it goes too high.

FIGURE 3.18 Horizontal Cross Section of the Spinal Cord, With Reflex Circuit.

A sensory neuron from the hand transmits signals (1) via the dorsal root of the spinal nerve into the spinal cord, where it (2) forms a reflex arc with a motor neuron that (3) exits through the ventral root and (4) activates the biceps muscle to flex the arm and withdraw the hand. The sensory input also travels (5) up to the brain to produce a sensation. (6) A motor neuron from the brain connects to the motor neuron in the ventral horn; this adds a voluntary activation of the muscle, though more slowly. (In reality, many neurons would be involved.)

Figures Brought to Life

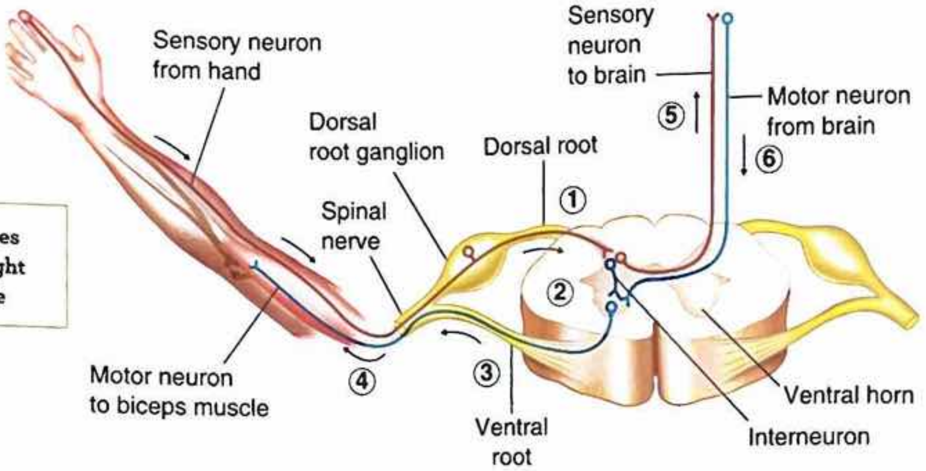
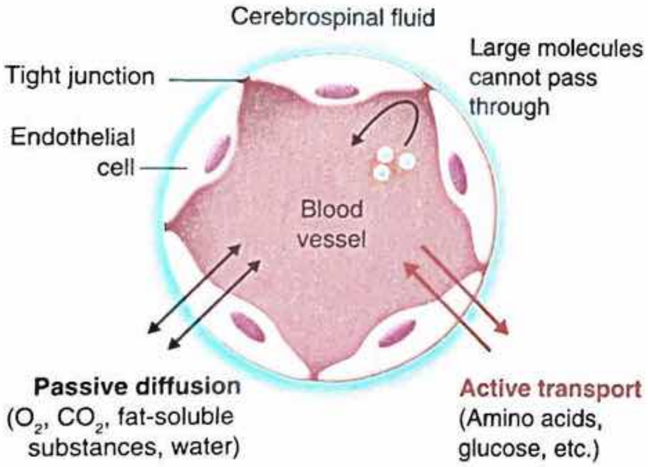


FIGURE 3.19 The Blood-Brain Barrier.

The tight junctions of the capillary walls prevent passage of large molecules into the brain. Small molecules, such as oxygen and carbon dioxide, pass through freely, as do fat-soluble substances, including most drugs. Water-soluble substances, such as amino acids and glucose, must be transported through the walls.


Cerebrospinal fluid
Tight junction
Large molecules cannot pass through
Endothelial cell
Blood vessel
Passive diffusion
(O₂, CO₂, fat-soluble substances, water)
Active transport
(Amino acids, glucose, etc.)

Protecting the Central Nervous System

The brain and the spinal cord are delicate organs, vulnerable to damage from blows and jostling, to poisoning by toxins, and to disruption by mislocated or excessive neurotransmitters. Both structures are enclosed in a protective three-layered membrane called the *meninges*. These meninges are the outermost dura layer, the arachnoid layer that separates the blood and the cerebrospinal fluid, and the innermost pia layer. Because the blood is below the tough dura layer, injuries to the head sometimes cause bruising below the dura, resulting in a subdural hematoma (blood-stone). The space between the arachnoid and the CNS is filled with cerebrospinal fluid, which cushions the neural tissue from the trauma of blows and sudden movement. The brain and spinal cord literally float in the cerebrospinal fluid, so the weight of a 1,200- to 1,400-g brain is in effect reduced to less than 100 g. The tough meninges and the cerebrospinal fluid afford the brain some protection from occasional trauma, but the *blood-brain barrier*, which limits passage between the bloodstream and the brain, provides constant protection from toxic substances and from neurotransmitters circulating in the blood, such as norepinephrine, which increases during stress.

Outside the brain, the cells that compose the walls of the capillaries (small blood vessels) have gaps between them that allow most substances to pass rather freely. In the brain, these cells are joined so tightly that easy passage is limited to small molecules, such as carbon dioxide and oxygen, and to substances that can dissolve in the lipid (fat) of the capillary walls (Figure 3.19). Fat solubility accounts for the effectiveness of most drugs, both therapeutic and abused. Most substances needed by the brain are water soluble and cannot pass through on their own, so glucose, iron, amino acids (the building blocks that proteins are made of), and many vitamins must be actively carried through the walls by specialized transporters.

Not all brain areas are protected by the barrier, however. This is particularly true of brain structures surrounding the ventricles. One of them is the area postrema; when you ingest something toxic, such as an excess of alcohol, the substance passes from the bloodstream into the area postrema. Because the area postrema induces vomiting, your stomach empties quickly—ideally before too much harm is done. This is why the postrema is called the "vomit center" of the brain.

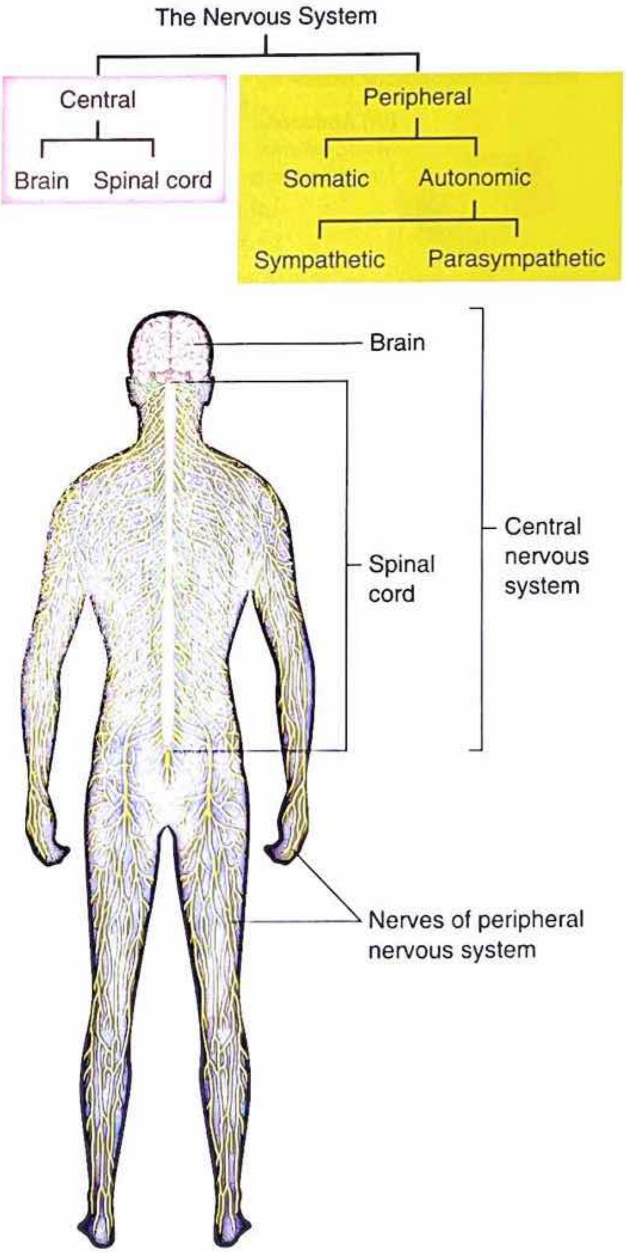
CONCEPT CHECK

Take a Minute to Check Your Knowledge and Understanding

- What is the advantage of the convoluted structure of the cortex?
- What has been the fate of psychosurgery? What clue from past experience did doctors have that lobotomy in particular might have undesirable consequences?
- Select one of the lobes or the midbrain or the hindbrain and describe the structures and functions located there.
- Describe the pathway of a reflex, identifying the neurons and the parts of the spinal cord involved.

FIGURE 3.20 Divisions of the Nervous System.

Source: Adapted from *Biological Foundations of Human Behavior*, by J. Wilson, 2003, Belmont, CA: Wadsworth.



The Peripheral Nervous System

The *peripheral nervous system (PNS)* is made up of the *cranial nerves*, which enter and leave the underside of the brain, and the *spinal nerves*, which connect to the sides of the spinal cord at each vertebra. From a functional perspective, the PNS can be divided into the somatic nervous system and the autonomic nervous system. The *somatic nervous system* includes the motor neurons that operate the skeletal muscles—that is, the ones that move the body—and the sensory neurons that bring information into the CNS from the body and the outside world. The *autonomic nervous system (ANS)* controls smooth muscle (stomach, blood vessels, etc.), the glands, and the heart and other organs. The diagram in Figure 3.20 will help you keep track of these divisions and relate them to the CNS. We dealt with the spinal nerves when we discussed the spinal cord, and we have said all we need to for now about the somatic system, so we will give the rest of our attention to the cranial nerves and the ANS.

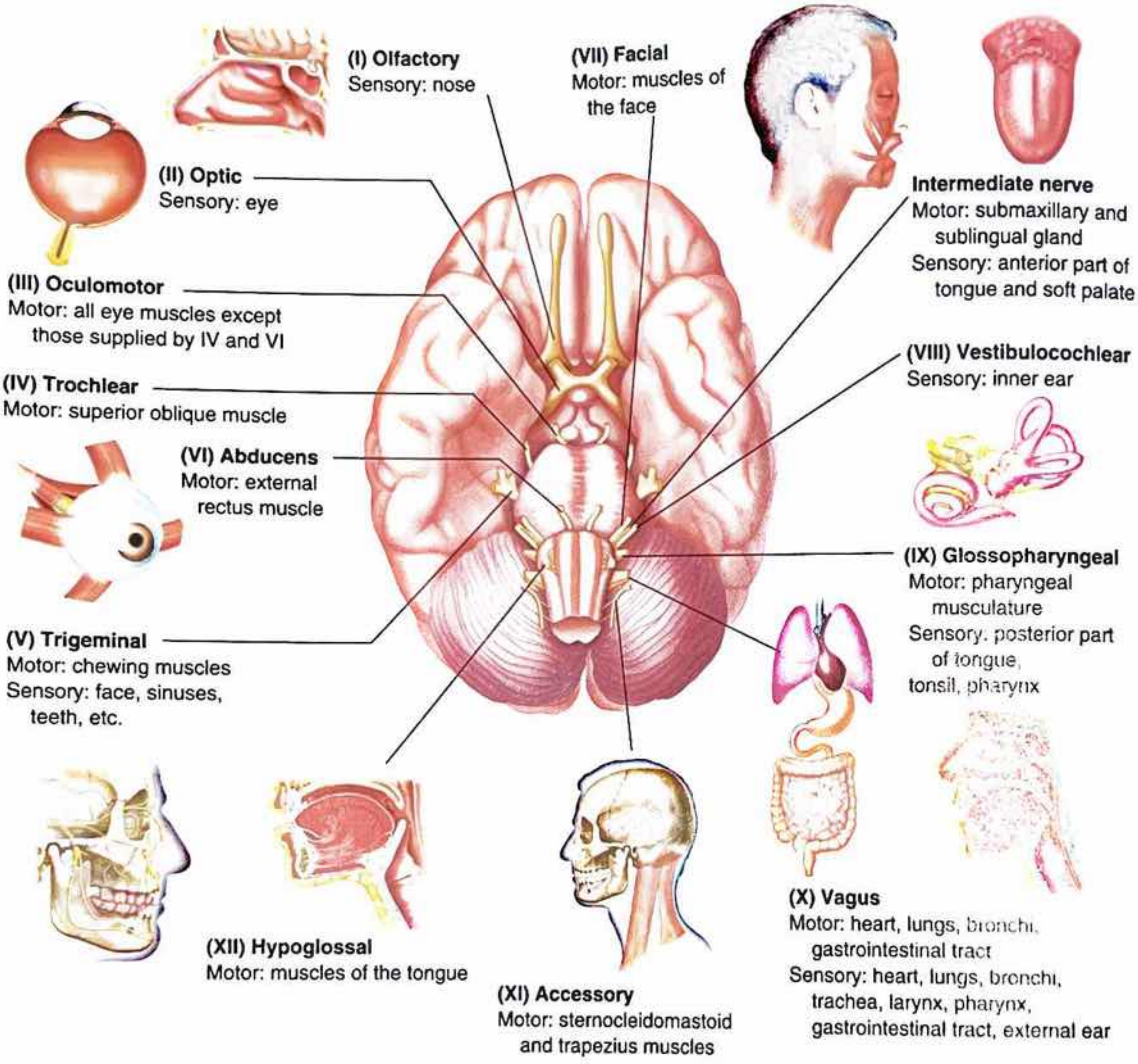
The Cranial Nerves

The cranial nerves enter and exit from the ventral side of the brain (Figure 3.21). Whereas the spinal nerves are concerned exclusively with sensory and motor activities

FIGURE 3.21 Ventral View of the Brain Showing the Cranial Nerves and Their Major Functions.

Brain landmarks are labeled to help you locate the nerves.

Source: Encyclopaedia Britannica/Contributor/Universal Images Group/Getty.


(I) Olfactory
Sensory: nose
(VII) Facial
Motor: muscles of the face
(II) Optic
Sensory: eye
Intermediate nerve
Motor: submaxillary and sublingual gland
Sensory: anterior part of tongue and soft palate
(III) Oculomotor
Motor: all eye muscles except those supplied by IV and VI
(VIII) Vestibulocochlear
Sensory: inner ear
(IV) Trochlear
Motor: superior oblique muscle
(VI) Abducens
Motor: external rectus muscle
(IX) Glossopharyngeal
Motor: pharyngeal musculature
Sensory: posterior part of tongue, tonsil, pharynx
(V) Trigeminal
Motor: chewing muscles
Sensory: face, sinuses, teeth, etc.
(X) Vagus
Motor: heart, lungs, bronchi, gastrointestinal tract
Sensory: heart, lungs, bronchi, trachea, larynx, pharynx, gastrointestinal tract, external ear
(XII) Hypoglossal
Motor: muscles of the tongue
(XI) Accessory
Motor: sternocleidomastoid and trapezius muscles

within and on the surface of the body, some of the cranial nerves convey sensory information to the brain from the outside world. Two of these, the olfactory nerves and the optic nerves, are often considered part of the brain. One reason for this special status is the brainlike complexity of the olfactory bulb and of the retina at the back of the eye; another is that their receptor cells originate in the brain during development and migrate to their final locations. As a consequence, the olfactory and optic nerves are sometimes referred to as *tracts*.

The Autonomic Nervous System

The functions of the ANS are primarily motor; its sensory pathways provide internal information for regulating its own operations. The ANS is composed of two branches. The *sympathetic nervous system* activates the body in ways that help it cope with demands such as emotional stress and physical emergencies. Your most recent emergency may have been when you overslept on the morning of a big exam. As you raced to class, your heart and breathing sped up to provide your body the resources it needed. Your blood pressure increased as your peripheral blood vessels constricted, shifting blood supply to the internal organs and your brain. Your muscles tensed to help you act, and your sweat glands started releasing sweat to cool your suddenly overheating body. All this activity was just the sympathetic nervous system at work. The *parasympathetic nervous system*, on the other hand, slows the activity of most organs to conserve energy but also activates digestion to renew energy. These two systems act like a seesaw; when one increases in activity, the other decreases.

? What are the functions of the autonomic nervous system?

The sympathetic branch arises from the middle (thoracic and lumbar) areas of the spinal cord (Figure 3.22; see Figure 3.17 for a refresher). Most sympathetic neurons pass through the *sympathetic ganglion chain*, which runs along each side of the spine; there they synapse with postsynaptic neurons that rejoin the spinal nerve and go out to the muscles and glands they serve. (Others pass directly to ganglia in the body cavity before synapsing.) Because most of the sympathetic ganglia are highly interconnected in the sympathetic ganglion chain, this system tends to respond as a unit. Thus, when you were rushing to your exam, your whole body went into hyperdrive. As you can see in Figure 3.22, the parasympathetic branch rises from the extreme ends of the PNS—in the cranial nerves and in the spinal nerves at the lower (sacral) end of the spinal cord. The parasympathetic ganglia are not interconnected but are located on or near the muscles and glands they control; as a result, the components of the parasympathetic system operate more independently than those of the sympathetic system.

Organs are innervated by both branches of the ANS, except for the sweat glands, the adrenal glands, and smooth muscles that constrict blood vessels (these receive only sympathetic activation). It is not accurate to assume that one branch is active at a time and the other completely shuts down. Rather, both are active to some degree all the time, and the body's general activity reflects the balance between sympathetic and parasympathetic stimulation.

CONCEPT CHECK

Take a Minute to Check Your Knowledge and Understanding

- Which cranial nerves are sometimes referred to as tracts, and why?
- Why does the sympathetic system operate more as a unit than the parasympathetic system does?
- How do the two branches of the ANS interact to regulate internal activity?

Development and Change in the Nervous System

Nothing rivals the human brain in complexity, which makes the development of the brain the most remarkable construction project that you or we can imagine. During development, its 100 billion neurons must find their way to destinations throughout the brain and the spinal cord; then they must make precise connections to an average of 1,000 target cells each (Tessier-Lavigne & Goodman, 1996). How this is accomplished is one of the most intriguing mysteries of neurology, but it is a mystery that is being solved a little at a time.

The Stages of Development

You already know that the nervous system begins as a hollow tube that later becomes the brain and the spinal cord. The nervous system begins development when the surface of the embryo forms a neural groove (Figure 3.23). The edges of this groove curl upward until they meet, turning the groove into a neural tube. Development of the nervous system then proceeds in four distinct stages: cell proliferation, migration, circuit formation, and circuit pruning.

Brain & Behavior

An Introduction to Behavioral Neuroscience

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